

ULTRA HIGH ENERGY COSMIC RAY AND γ -RAY SIGNATURES OF INDUCTIVE ACCELERATION IN AGN JETS

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ABSTRACT

The highest energy cosmic rays could be produced by drifts in magnetized, cylindrically collimated, sheared jets of powerful active galaxies (i.e. FR II radiogalaxies; radio loud quasars and high power BL Lacs). We show that in such scenarios proton synchrotron radiation can give rise to detectable photon fluxes at energies ranging from hundreds of keV to tens of MeV.

Subject headings: AGNs-UHECRs-CGRO-COMPTEL-EGRET-INTEGRAL-GLAST-OSSE-SIGMA

1. INTRODUCTION

Proton-synchrotron emission has been considered in the past in a context involving X-ray flares in Markarian and in attempts at explaining the diffuse X-ray background (Muecke&Protheroe 1999; Aharonian 2002). Here we investigate the synchrotron emission from UHE protons accelerated in AGN jets by a novel mechanism involving inductive fields (Lyutikov&Ouyed 2005, hereafter LO5). This is a scheme of Ultra-High Energy Cosmic Ray (UHECR) acceleration due to drifts in magnetized, cylindrically collimated, sheared jets of powerful active galaxies (with jet power in Poynting flux $\geq 10^{46}$ erg s⁻¹) - It is important to note that the acceleration mechanism suggested in LO5 is associated with the jets of AGNs, and not with their hot spots. We pointed out in LO5 that a positively charged particle carried by such a plasma is in an unstable equilibrium if $\mathbf{B} \cdot \nabla \times \mathbf{v} < 0$, so that kinetic drift along the velocity shear would lead to fast, *regular* energy gain; here \mathbf{B} is the jet magnetic field dominated by the toroidal component while \mathbf{v} is indirectly related to the angular velocity of the black-hole-accretion disk system driving the jet and is falling off with the cylindrical radius. We showed that if a seed of pre-accelerated particles with energy below the ankle $\leq 10^{18}$ eV is present, these particles can be boosted to energies above 10^{19} eV. A key feature of the mechanism is that the highest rigidity particles are accelerated most efficiently implying the dominance of light nuclei for extragalactic cosmic rays in our model: from a mixed population of pre-accelerated particle the drift mechanism picks up and boosts protons preferably.

In this acceleration mechanism synchrotron radiation is thus a natural outcome since the protons escape the jet sideways in a direction transverse to the magnetic field in the jet. In this letter we propose that the resulting radiation spectrum makes an attractive interpretation of non-thermal X-ray and γ -ray emission from powerful AGNs

and might be a direct indication of inductive acceleration in AGN jets as a viable mechanism for UHECR acceleration.

2. SYNCHROTRON EMISION

At a distance r from the central engine producing X-rays of energy ϵ with a luminosity L_X , the density of these X-ray photons is

$$n_X \simeq \frac{L_X}{4\pi r^2 \epsilon} \sim 1.7 \times 10^{-6} \text{ cm}^{-3} \quad (1)$$

$$\times \left(\frac{L_X}{10^{47} \text{ ergs}^{-1}} \right) \left(\frac{\epsilon}{10 \text{ keV}} \right)^{-1} \left(\frac{r}{\text{Mpc}} \right)^{-2}.$$

For a proton- γ cross-section $\sigma_{N\gamma} \sim 100 \mu\text{b}$ the corresponding nucleon mean-free path in this X-ray background is

$$l_{N\gamma} \sim 1.9 \times 10^9 \text{ Mpc} \left(\frac{L_X}{10^{47} \text{ ergs}^{-1}} \right)^{-1} \left(\frac{\epsilon}{10 \text{ keV}} \right) \left(\frac{r}{\text{Mpc}} \right)^2. \quad (2)$$

The cross-section for inverse Compton (IC) scattering is on the other hand $\sigma_{IC} \sim 2 \times 10^{-31} \text{ cm}^2$, corresponding to a length scale

$$l_{IC} \sim 9.3 \times 10^{11} \text{ Mpc} \left(\frac{L_X}{10^{47} \text{ ergs}^{-1}} \right)^{-1} \left(\frac{\epsilon}{10 \text{ keV}} \right) \left(\frac{r}{\text{Mpc}} \right)^2. \quad (3)$$

The optical depth for pp interaction in the vicinity of the AGN is much smaller than one. This implies that the neutrino flux is much smaller than the cosmic ray flux and therefore should not be detected in the foreseeable future. The sensitivity of ICECUBE to the neutrino power of a source at distance D is $\sim 2 \times 10^{45} \text{ ergs}^{-1} (D/100 \text{ Mpc})^2$ (Ahrens et al. 2004).

We are left with synchrotron losses which occur on a length scale of

$$l_B \sim 430 \text{ kpc} \left(\frac{E_p}{10^{20} \text{ eV}} \right)^{-1} \left(\frac{B}{\text{mG}} \right)^{-2}, \quad (4)$$

where we take qualitatively the jet magnetic field to be of the order of $\sim 100 \mu\text{G}$ – 10 mG (e.g. Sikora et al. 1997; Aharonian 2001; Stawarz et al. 2005; Schwartz et al. 2006).

The photon energy fluence peaks at the energy (Lang 1980)

$$E_{\text{sync}} \sim 25 \text{ MeV} \left(\frac{E_p}{10^{20} \text{ eV}} \right)^2 \left(\frac{B}{\text{mG}} \right), \quad (5)$$

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and since in the model of LO5,

$$E_p \lesssim 4 \times 10^{20} \left(\frac{L_P}{10^{46} \text{ erg s}^{-1}} \right)^{1/2} \text{ eV}, \quad (6)$$

where L_P is the Poynting flux luminosity of the AGN, this implies

$$E_{\text{sync}} \lesssim 400 \text{ MeV} \left(\frac{L_P}{10^{46} \text{ erg s}^{-1}} \right) \left(\frac{B}{\text{mG}} \right). \quad (7)$$

It is important to note that in the model of LO5 the accelerating potential is defined by the Poynting flux luminosity, which in some sources (with high dissipation rates) might exceed the *observed* bolometric luminosity; intrinsically of course the Poynting flux is always smaller than the total luminosity.

Let us define f_γ as the fraction of the luminosity L_{UHECR} of accelerated UHECR that goes into γ -rays around the energy given by eq. (5). If l_{ext} is the lateral extent of the jet over which the protons are accelerated, one has $f_\gamma \sim l_{\text{ext}}/l_B$ for $l_{\text{ext}}/l_B \ll 1$. Given that typical jet width is of the order of 0.1-1 kpc (Hughes 1991) it implies a range of.

$$f_\gamma \sim 10^{-2} \left(\frac{l_{\text{ext}}}{1 \text{ kpc}} \right) \left(\frac{L_P}{10^{46} \text{ erg s}^{-1}} \right)^{1/2} \left(\frac{B}{\text{mG}} \right)^2. \quad (8)$$

These photons can leave the jet with negligible interactions: First, photons of energy given by eq. (5) are below the threshold for pair production with $\sim 10 \text{ keV}$ X-ray photons. Second, with l_j the jet length, the density of synchrotron γ -rays is

$$n_\gamma \sim \frac{f_\gamma L_{\text{UHECR}}}{2\pi E_{\text{synch}} l_j l_{\text{ext}}} \sim 3.5 \times 10^{-6} \text{ cm}^{-3} \quad (9)$$

$$\times \left(\frac{f_\gamma L_{\text{UHECR}}}{10^{45} \text{ erg s}^{-1}} \right) \left(\frac{1 \text{ MeV}}{E_{\text{synch}}} \right) \left(\frac{100 \text{ kpc}}{l_j} \right) \left(\frac{1 \text{ kpc}}{l_{\text{ext}}} \right),$$

which is comparable or smaller than Eq. (1) and, therefore, does not modify the proton interactions. With $\sigma_T \simeq 6.7 \times 10^{-25} \text{ cm}^2$ the Thomson cross section, the optical depth for pair production among these photons is thus $\tau_{\gamma\gamma} \sim \sigma_T n_\gamma l_{\text{ext}} \ll 1$.

Below the energy given by eq. (5), the synchrotron spectrum of a single proton scales as $E^2 j_{\text{synch}}(E) \propto E^{4/3}$, whereas it cuts off exponentially above E_{synch} . The total synchrotron power of a proton of energy E_p scales as E_p^2 . Folding with a charged primary spectrum $j_p(E_p) \propto E_p^{-\gamma}$, this yields a synchrotron flux $E^2 j_{\text{synch}}(E) \propto E^{-(\gamma-3)/2}$ up to E_{synch} for the highest energy protons. In the model of LO5, in the extreme case of an infinite potential, $\gamma \simeq 2$ and thus $E^2 j_{\text{synch}}(E) \propto E^{1/2}$ or, a spectrum $j_{\text{synch}}(E) \propto E^{-1.5}$. Depending on composition and whether the ankle in the cosmic ray spectrum is due to a cross-over from a galactic to an extragalactic population, the source injection spectral index is $2.3 \lesssim \gamma \lesssim 2.7$ (see, e.g., Berezhinsky et al. 2006; Allard et al. 2007). In our model softer injection spectra with $\gamma > 2$ are more realistic since the potential might only be used partially during the inductive acceleration process. Note that the synchrotron spectrum is not sensitive to the low energy continuation of the primary spectrum as long as $\gamma \lesssim 3$.

3. γ -RAY SIGNATURES

For a point source power L_{UHECR} at distance D this results in a γ -ray point flux of

$$E_{\text{sync}}^2 j_s(E_{\text{sync}}) \simeq 8 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1} \quad (10)$$

$$\times f_\gamma \times \left(\frac{L_{\text{UHECR}}}{10^{45} \text{ erg s}^{-1}} \right) \left(\frac{D}{100 \text{ Mpc}} \right)^{-2},$$

where $10^{45} \text{ erg s}^{-1}$ is about $\sim 1\%$ of the bolometric luminosity of the brightest AGNs and about 10% of the jet power $L_P \gtrsim 10^{46} (E_{\text{max}}/4 \times 10^{20} \text{ eV})^2 \text{ erg s}^{-1}$ required to accelerate protons up to E_{max} of a few 100 EeV in the scenario of LO5. Given that $f_\gamma \sim 10^{-4}$ – 10^{-1} , this implies that the point and diffuse fluxes are within the sensitivities of existing and upcoming instruments such as COMPTEL (0.75-30 MeV), EGRET (30 MeV - 20 GeV), SIGMA, INTEGRAL and GLAST GRB monitor (10 keV - 25 MeV). Note that Eq. (10) is just the angle-averaged flux; since for simplicity we assume that the synchrotron radiation is strongly beamed perpendicular to the jet, in which case the actual flux will strongly depend on jet orientation. In reality however the direction of the synchrotron emission depends on the structure of the magnetic field and its degree of entanglement as well as aberration effects.

As discussed in LO5, requirements on luminosity (and the assumption of a high proton content in UHECRs) excludes low power nearby sources, like the nearest AGN M87 and the starburst galaxy M82. Instead high power radio galaxies with $L \gtrsim 10^{45} \text{ erg s}^{-1}$ (e.g. FR II radio-galaxies; radio loud quasars and high power BL Lacs) at intermediate distances are favored, such as Pictor A ($z = 0.035$), PKS 1333-33 ($z = 0.0124$), PKS 2152-69 ($z = 0.027$), PKS 1343 ($z = 0.012$), and the Seyfert galaxy 3C 120 ($z = 0.033$). It is still worth considering high power FRI as possible candidates in case as we have said their Poynting power turns out to exceed the *observed* bolometric value. For example, Centaurus A, the nearest giant radio galaxy at a distance of $\sim 3.6 \text{ Mpc}$ with a jet pointing with $\sim 70^\circ$ to the line of sight has been seen by SIGMA and COMPTEL. It has a γ -ray spectrum somewhat harder than E^{-2} , roughly consistent with the $E^{-(\gamma+1)/2}$ γ -ray spectrum with $2 \lesssim \gamma \lesssim 3$, suggested by the mechanism discussed here, cutting off above a few MeV. The (time variable) flux around 100 keV is $\sim 2 \times 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1}$ (Bond et al. 1996, Sreekumar 2000). From Eq. (10), this flux density would imply $f_\gamma (L_{\text{UHECR}}/10^{43} \text{ erg s}^{-1}) \gtrsim 2.8\%$. Thus for this source the fraction of L_{UHECR} luminosity that goes into γ -rays is a few percents, larger than the value derived from equation (8): Indeed, the total high energy (we take as Poynting) luminosity of Cen A is estimated to $\sim 10^{43} \text{ erg s}^{-1}$ (Bond et al. 1996, Israel 1998), and thus $f_\gamma \lesssim 3 \times 10^{-4} (l_{\text{ext}}/\text{kpc})(B/\text{mG})^2$. This discrepancy is likely less stringent for emission beamed toward the observer which may be the case since the jet is seen almost sideways; a larger $l_{\text{ext}} B^2$ could also remedy to this discrepancy. The maximal UHECR energy is thus $E_p \sim 10^{19} \text{ eV}$. This implies $E_{\text{synch}} \sim 200 \text{ keV}$ according to Eq. (5) if L_{UHECR} is comparable, which could thus explain the $\sim 100 \text{ keV}$ flux with f_γ of a few percent.

Blazars are of particular interest to our model since they are known to show a spectral bending (i.e. spectral index break) around a few MeV to tens of MeV ener-

gies. Combination of OSSE, COMPTEL and EGRET data show a spectral bending during the low luminosity and high-luminosity γ -ray state of some sources with a break energy estimated to range between ~ 1 MeV and ~ 20 MeV (e.g. Kurfess 1994; Collmar et al. 1997). This break energy lies within the range predicted in our model [see eqs (5) and (7)]. Furthermore, in time-averaged analyses the spectra of these AGNs are well described by power-law shapes ($E^{-\alpha}$) with a photon index α of the order of 2 which can be accounted for in our model. We note however that blazars are at high enough redshift to lie beyond the GZK cut-off. Thus, these γ -ray signatures (which we argue might be indicative of the inductive acceleration mechanism) will have associated UHECRs at

most below $\sim 5 \times 10^{19}$ eV.

If powerful AGNs collectively explain the observed UHECR flux then their volume emissivity above $\simeq 10^{19}$ eV is roughly of the order of $Q_{\text{UHECR}} \sim 10^{37}$ erg $\text{Mpc}^{-3} \text{s}^{-1}$, and one obtains a diffuse gamma ray flux of

$$E_{\text{sync}}^2 j_{\text{d}}(E_{\text{sync}}) \simeq f_{\gamma} \times 3 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \\ \times \left(\frac{Q_{\text{UHECR}}}{10^{37} \text{ erg Mpc}^{-3} \text{ s}^{-1}} \right). \quad (11)$$

With $f_{\gamma} \sim 1\%$, the diffuse flux predicted from our scenario could thus also contribute a fraction of a few percent to the diffuse flux observed by COMPTEL, $\sim 3 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ (Sreekumar 2000).

REFERENCES

- Aharonian, F. A. 2001, *Mon.Not.R.Astron.Soc.*, 332, 215
 Ahrens, J. 2004, *Astropart. Phys.* 20, 507
 Allard, D., A. V. Olinto, A. V., & and Parizot, E.,
 arXiv:astro-ph/0703633.
 Berezhinsky, V., Gazizov, A., & Grigorieva, S. 2006, *Phys. Rev. D*,
 74, 043005
 Bond, L. A. 1996, *A & A* 307, 708
 Collmar, W. et al. 1997, *A&A*, 328, 33
 Hughes, P. A. 1991, *Beam and Jets in Astrophysics* (Cambridge
 University Press)
 Israel, F. P. 1998, *Astron. Astrophys. Rev.* 8, 237
 Kurfess, J. D. 1994, *Compton Observatory Observations of AGNs*,
 IAU Symposium, 159, 39
 Lang, K. R. 1980, “*Astrophysical Formulae*”, Springer.
 Lyutikov, M., & Ouyed, R. 2007, *Astropart. Phys.*, 27, 473
 [astro-ph/0507620] [LO5]
 Mücke, A., & Protheroe, R. J. 1999, astro-ph/9910460
 Schwartz, D. A. et al. 2006, *ApJ*, 640, 592
 Sikora, M., Madejski, G., Moderski, R., & Poutanen, J. 1997, *ApJ*,
 484, 108
 Sreekumar, P. 2000, *AIP Conference Proceedings*, 510, 459.
 Stawarz, L., Siemiginowska, A., Ostrowski, M., & Sikora, M. 2005,
ApJ, 626, 120